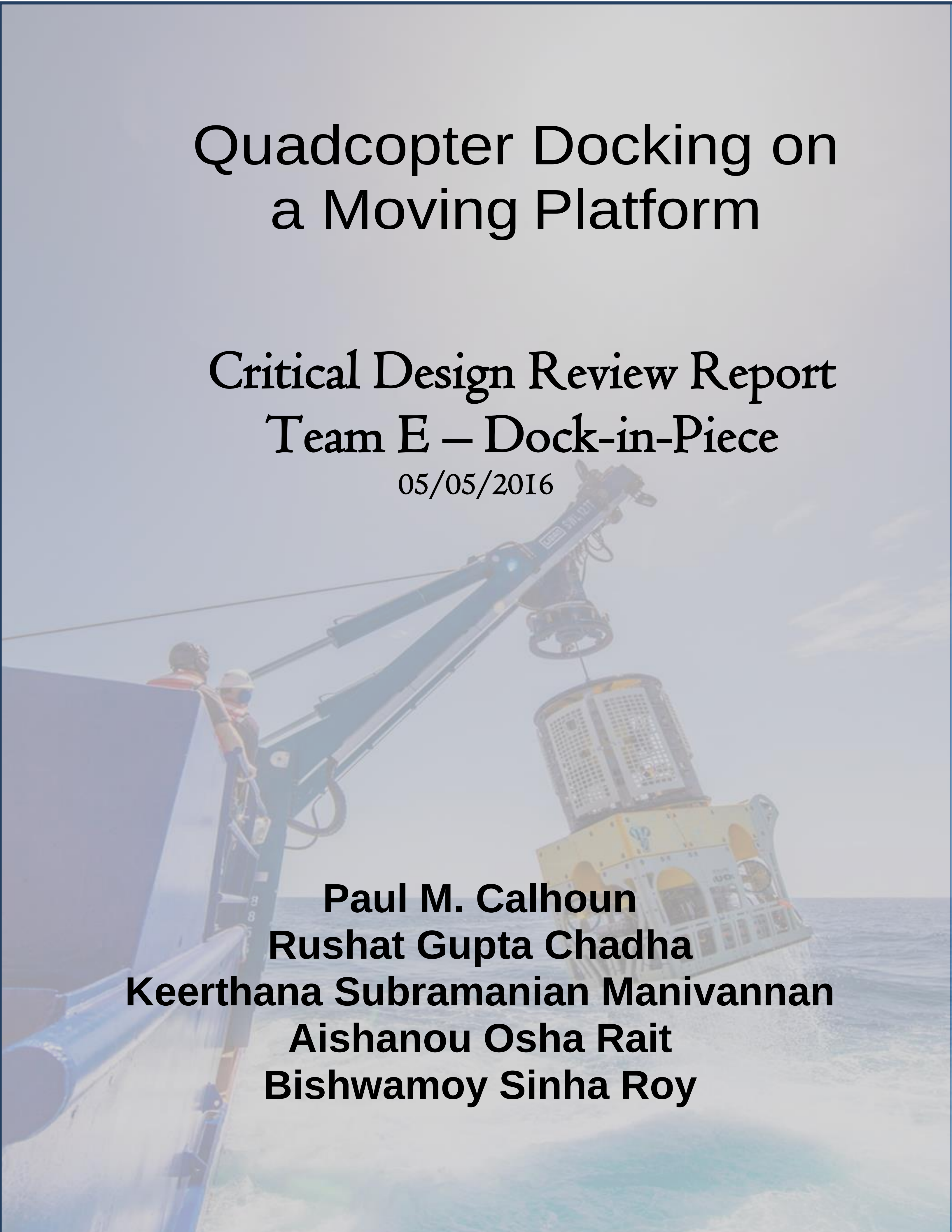


Quadcopter Docking on a Moving Platform

Critical Design Review Report
Team E – Dock-in-Piece

05/05/2016

Paul M. Calhoun
Rushat Gupta Chadha
Keerthana Subramanian Manivannan
Aishanou Osha Rait
Bishwamoy Sinha Roy

MRSD Project – Dock-in-Piece

December 17, 2015

Abstract

Our problem statement is inspired by the challenges faced by FMC Technologies Schilling Robotics personnel, while docking their Remote Operated Vehicle (ROV) to the Tether Management System (TMS). The ROV detaches and deploys from the bottom of the TMS when the system is at depth. The TMS is negatively buoyant and is suspended from a ship. As the ship heaves on the surface of the water, the TMS heaves up and down with a slight lateral motion. ROV Operators must dock and latch the ROV to the underside of the moving TMS before resurfacing. This can be very challenging for even experienced operators. Autonomous docking is the core problem we aim to solve. Through this project we will demonstrate the autonomous docking of a quadcopter to the underside of a suspended moving platform. The underwater environment will be simulated by functioning in a GPS degraded environment. At the end of the project, we were docking autonomously to a moving overhead platform, with the quadcopter acting completely autonomously until docking occurred, including landing if the dock was moving faster than was considered safe. The details of our design and implementation are outlined in this report.

MRSD Project – Dock-in-Piece

December 17, 2015

Table of Contents

MRSD Project – Dock-in-Piece

December 17, 2015

1 Introduction

Our problem statement is inspired by the challenges faced by FMC Technologies Schilling Robotics personnel while docking their Remotely Operated Vehicle (ROV) to the Tether Management System (TMS). The ROV detaches and deploys from the bottom of the TMS when the system is at depth. The TMS is negatively buoyant and is suspended from a ship. As the ship heaves on the surface of the water, the TMS heaves up and down with a slight lateral motion. ROV Operators must dock and latch the ROV to the underside of the moving TMS before resurfacing. This can be very challenging for even experienced operators. Collisions frequently damage the ROV and TMS. The tether is sometimes compressed between the ROV and the TMS, which degrades the communication and power supply between the TMS and the ROV. At times, the tether breaks and the ROV falls to the bottom of the seabed, resulting in the need for another ROV to be deployed to bring it back.

2 Project Description

Through this project, we demonstrated the autonomous docking of a quadcopter to the underside of a suspended moving platform. This model approximated the subsea system of ROV and TMS, complete with determining the safe conditions to dock and providing mechanical latching system that minimizes the forces between the quadcopter and the platform. The platform moves up and down in a sinusoidal motion which is analogous to the TMS which bobs up and down under the sea, and the quadcopter is analogous to the ROV. The project focuses on more on the prediction system which predicts an optimal moment to dock rather than the locking or mechanical aspects of the ROV-TMS system. The underwater environment is simulated by functioning in a GPS degraded environment.

3 Use Case

A developer at Schilling Robotics visits a trade fair and sees a retrofit kit that adds a minimal payload and the capability of autonomous docking to a platform moving in a single axis. Having several customers of his unmanned undersea vehicle branch who want a method of navigating to a tether management system with their underwater remotely operated vehicle, he purchases the retrofit. He reasons that it will be fun and possibly get him a pay point on his next performance cycle if he can demonstrate its usefulness to his supervisor. He purchases the retrofit and declines to fill out a customer survey asking him what further features he wants to see in the next version, since this one has all the features he wants already.

He receives the kit and spends a weekend setting up a dock as shown in figure 1. The addition of the software changes to his Phantom 2 takes a few minutes and the hardware install is almost as swift. It’s a windy day and the tree he’d tied his platform to was swaying quite a bit, and after his initial disappointment at the app telling him it was impossible to dock in those conditions, repeatedly mashing the ‘dock’ button finally proved effective and the drone successfully attaches itself to the dock without running into the tree. It even weaves around his bird feeder and succeeds in avoiding a starling that appeared intent on driving the drone out of the air. He is pleased that the retrofit is light and not very cumbersome.

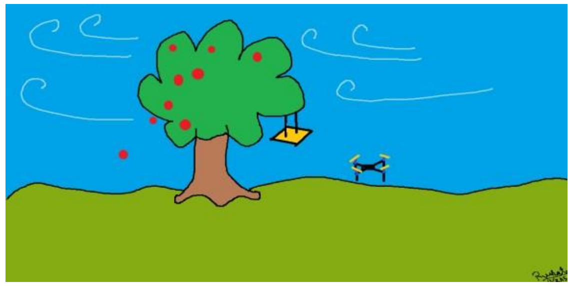


Figure 1 Quadcopter and Platform in adverse environment

The developer secures funding from his supervisor and contacts the student team who launched the retrofit into a full product. Though hesitant at first, they engage an attorney and draw up a limited use contract for the TDP of the docking kit. The developer is happy, his boss less so when he sees what kind of royalties the developer had agreed to, and the developer realizes he's going to have to work very hard for that pay point. He gets going and succeeds in adapting the code for his customers' ROV and TMS. On its first test, the ROV collides with an undersea vent. However, the entire test is invalidated when they discover an octopus had attached itself to the ROV camera and that a warning had been displayed by the adapted software, but not where the ROV operator is used to viewing warnings and cautions.

Finally, launch day arrives and the customer is pleased at the results. The ROV docks without needing the use of a heave-compensated winch. The ROV smoothly detaches from the TMS, goes about its mission, and returns to be hauled up on the TMS without incident (figure 2). The customer is also very happy with the user interface, which is a single toggle button, removing the need for lengthy training and decreasing the costs of using the ROV, since the operators don't have to be as skilled at docking any more. The developer gets a bonus from his supervisor, an angry letter from the sailors' union, and a bill from the UAV kit developers after an independent audit.

Figure 2 Successful Retrieval of the ROV

Future deployments of ROV systems aboard ships include the changes and a program to make sure the necessary changes is implemented on legacy ROV carriers as they are brought in for routine maintenance.

4 System level requirements

4.1 Mandatory Requirements

4.1.1 Functional Requirements

- The system shall

MF1. Have two major components: a quadcopter and a moving platform

MF2. Detect and communicate when docking is not possible

- The docking platform shall

MF1.1 Be moving in a single axis (z-direction) until the quadcopter has been docked

MF1.2. Oscillate in harmonic motion with dominant frequency < 0.3Hz

MF1.3. Have oscillations' span ±200mm

- The quadcopter shall

MF2.1. Localize w.r.t. platform within 50mm accuracy

MF2.2 Plan a path to the docking platform

MF2.2 Generate a trajectory from the starting position to the platform

MF2.3 Navigate to the platform

MF2.4. Dock to the platform autonomously and without colliding (collision defined as relative velocity of the quadcopter with respect to the dock of 50 cm/s) within 10 minutes

4.1.2 Non-Functional Requirements

- The system shall

MNF1. Function in a GPS degraded environment

MNF2. Be easy to operate, maintain, and repair

MNF3. Provide a user interface status of docking

MNF4. Cost less than $3,000 to own over its life cycle

- The quadcopter shall

MNF2.1 Have a payload capacity of > 500g

- The platform shall

MNF3.1 Have a locking mechanism which supports weight of 5kg

4.2 Desirable Requirements

4.2.1 Functional Requirements

- The docking platform will

DF1.1. Have 3 degrees of freedom along X, Y and Z-direction

DF1.2. Oscillate in harmonic motion with dominant frequency of greater range

4.2.2 Non Functional Requirements

- The docking platform will

  DNF1.2. Have random movements in 3D space

- The quadcopter will

  DNF2.1. Dock to the platform within 5 minutes

5 Functional Architecture

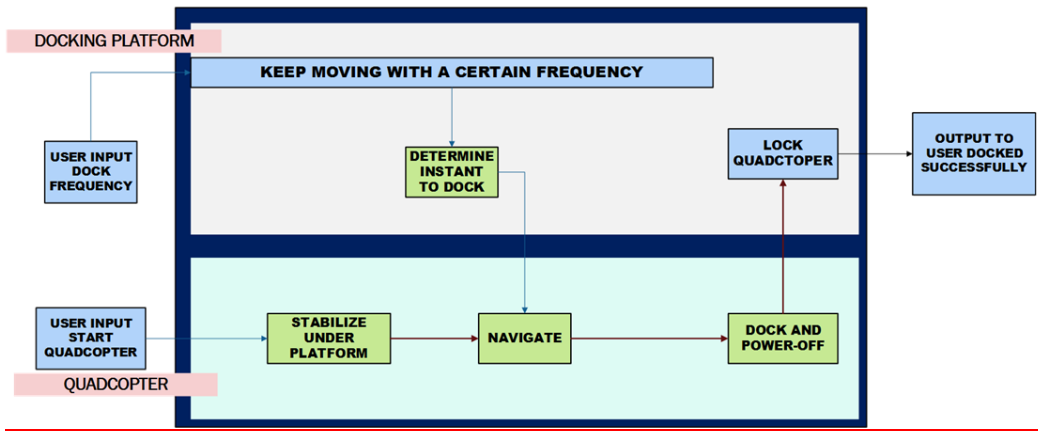


Figure 3 Functional Architecture of the Docking process

The system's input is the user's decision to dock and the output is the successful dock. The architecture is divided into three parts - the quadcopter, the platform, and the Palantir. The subsystems work together to plan the approach to the docking platform and dock at an opportune moment. The moment to dock is determined by the Palantir. There are three phases in the whole docking process. (Figure 3)

5.1 Initiation Phase

During this phase the user initiates the docking sequence by beginning the program, which allows the quadcopter to take off and stabilize at a safe distance below the moving platform. The safe distance is determined by hovering in place for 8-10s and watching the heave of the platform. The quadcopter, then, autonomously maintains the safe distance for the next phase.

5.2 Decision Phase

Once the quadcopter reaches the safe distance, the Palantir starts analyzing the IR data from the platform. Once enough data is received (10s), the Palantir runs its analysis to come up with the mating moment and communicates this instant with a approach velocity to the quadcopter. If docking isn't possible (frequency of the platform is higher than a modifiable threshold), the quadcopter lands. If docking is possible, the system moves to the docking phase.

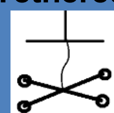
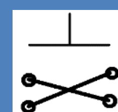
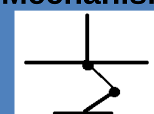
5.3 Docking Phase

When the quadcopter receives the time to mate and the velocity approach, it waits for the prescribed amount of time and begins its approach. It latches on using the locking mechanism (Velcro) and the final output is sent to the user that the quadcopter has been docked successfully and what the relative velocity between the quadcopter and dock was.

6 System Level Trade Studies

6.1 Overall System Design

Table 1 Overall System Trade Study

Category	Weightage (100%)	Tethered 	Non-Tethered 	Heave Compensating Mechanism 
Ease of Quadcopter Maneuverability	20	7	10	10
Customer Requirements	15	9	9	5
Mechanical Complexity	15	8	8	4
Scalability	15	8	8	3
Control Complexity	15	7	8	7
Cost	10	7	9	4
Chance of Failure	10	7	9	5
Total	**10**	**7.6**	**8.75**	**5.75**

An important thing which was kept in mind while deciding various system level designs was the fact that this project is a simulation of a real life problem. To deliver what our client needs, it is very important that this project is in line with their expectations, problems faced with the existing hardware. After brainstorming, the team has come up three system level solutions that are being judged by the 7 criteria shown in Table 1.

Of the three potential solutions, two were purely Quadcopter control based, while the other was a mechanical solution to be installed on the moving platform. While the sponsor gave the team a lot of flexibility on the range of possible solutions, a mechanical solution was strongly discouraged, primarily because of the scalability issue and the fact that mechanical appendages has lots of on-site maintenance problems. Since the team shared common interest in making the final product as implementable as possible, the heave compensating mechanical appendage was ruled out. A major decision that the team had to make was whether to use a tether on the Quadcopter or not. While using a tethered Quadcopter would be the closest simulation of the actual system, the low score in ease of Quadcopter maneuverability, which had the maximum weight, automatically ruled the tethered solution out. With a score of 8.75 on a scale of 10, a Non-Tethered Quadcopter using a purely control based approach which was also the most scalable and desired solution to the problem was chosen.

6.2 Docking Mechanism

Table 2 Trade Study of Docking Platform

Criteria	Weights	Geared Crank-Slider	Rack-Pinion	Ball Screw
Power Requirements	30	9	7	2
Ease of Operation	15	9	4	4
Ease of Manufacturability	20	4	4	8
Accuracy	15	9	6	8
Reliability of mechanism	20	7	4	9
TOTAL	**100**	**7.6**	**5.2**	**5.8**

To decide on the final dock design, various designs for possible docking platforms were prototyped. Since it was an integral part in the success of the project, we decided to make prototypes for each mechanism. These prototypes were tested on the criteria listed in the table above (Table 2) which is a trade study between the three prominent design solutions that were discussed.

As we made prototypes of the three mechanisms, the Rack and Pinion method caused the Pinion to slip with gravity acting on it. And to create a successful sinusoidal motion, the docking platform has to move in such a way that the gear doesn't slip. This method was rejected because it wasn't producing a proper sinusoidal motion.

Ball Screw method was ruled out because the Ball Screw was expensive, and it was not easy to operate with. The power requirements of a Ball Screw are very high as the platform has to move up against gravity in order to reach the top of the sinusoid.

Since the Geared Crank-Slider is more accurate in producing a sinusoidal motion and its power requirements are low and this is just a slider moving in a full circular motion which creates the sinusoidal motion of the platform, this mechanism was chosen to be the final dock design with a score of 7.6.

6.3 Quadcopter

Table 3 Quadcopter Trade Study

Category	Weightage (100%)	DJI Matrice 100 [4]	TurboAce Matrix	3DR solo	3DR X8+
Payload Capacity	20	8	9	4	7
Customizability of processor	15	8	1	7	7
Availability of an SDK	20	9	0	8	8
Documentation of SDK	20	9	0	8	8
Position of on Board Camera	10	8	9	4	4
Battery Life	5	8	8	6	4
Spares / availability	5	8	8	8	8
Cost	5	3	6	7	8
Total	10	8.35	4.35	6.9	7.45

The Quadcopter is the most important subsystem of this project, and the success of the project revolves around the Quadcopter's control. A carefully discussed set of criteria for the selection of a Quadcopter with their respective weights are illustrated in Table 3 .Three of these criteria played a significant role in the decision process: Payload capacity, availability of an SDK (Software Development Kit), and its Documentation. After filtering out hobby Quadcopters, the team narrowed down to 4 Quadcopters, suppliers of which are famous among the aerial vehicle community for various reasons like payload capacity and the SDK. However, 2 of these (TurboAce Matrix and 3DR solo), got ruled out because of lack of an SDK and low payload capacity.

A lengthy analysis based on reviews from users and developers led to the conclusion that even though the DJI Matrice 100 was more expensive, its add-ons, like preloaded flight algorithms, filtered sensor outputs, battery life, and excellent reviews would overall be a very big advantage for the team while troubleshooting sensor and hardware related problems. Since this was the most important part of our project, cost wasn't given a high weight and hence the DJI Matrice 100 won the trade study with a score of 8.35 on a scale of 10.

7 Cyber-physical Architecture

7.1 Docking Platform

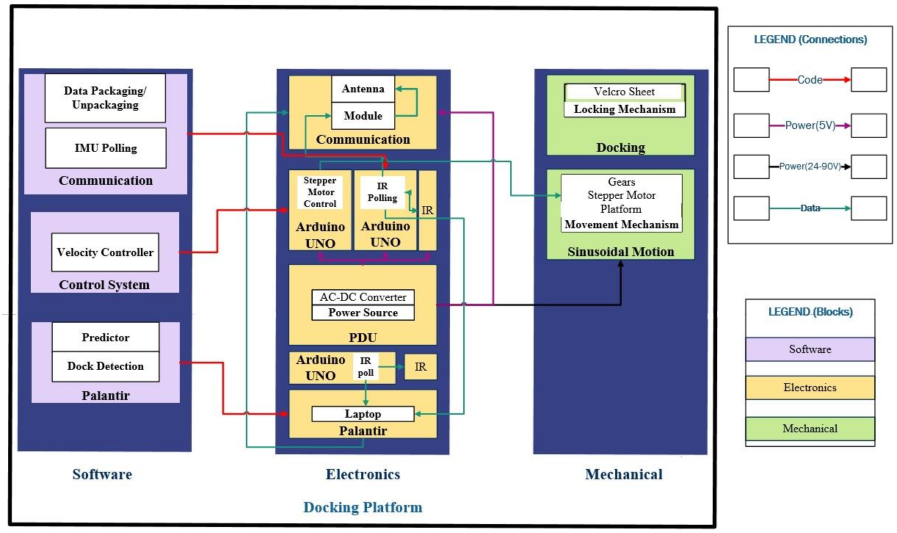


Figure 4 Cyber-physical Architecture for Docking Platform

The architecture, shown in Figure 4, is divided into three abstractions for the docking platform. The software abstraction encompasses the algorithms used to create the up-down harmonic motion of the platform at a user-defined frequency within a fixed range. It also processes the sensor readings from the IR to determine the frequency of platform motion. The electronics abstraction shows the different electrical equipment and electronic devices and their connections to run the algorithms from the software abstraction. It comprises of an IR sensor facing down, a set of four IR sensors facing orthogonal to the motion of the dock, three Arduino Unos, and stepper motor and driver for creating and sensing the platform motion. There are two different power supply voltages. The motor driver requires 24 V to 92 V DC and the Arduinos and sensors need 5V DC. The decision made by the Palantir subsystem is sent to the Quadcopter's SBC using a Wi-Fi module which comprises the communication block. The lines from the software abstraction show which processor runs the processes. There are three separate Arduinos: (1) for the motor speed control, (2) for processing sensor data, and (3) for monitoring the IR dock detection grid. Lastly, the mechanical abstraction holds the mechanisms that allow the software algorithms to manifest into the physical world. The stepper motor rotates the crank of the crank-slider mechanism which causes the slider and subsequently the platform to move up and down. The gear train is used to obtain high torques. For the locking mechanism, a Velcro pad is glued to the bottom of the platform. The Quadcopter attaches itself to the platform using the Velcro.

7.2 Quadcopter

Similar to the docking platform's sub-division, the cyberphysical architecture of the Quadcopter is divided into three subsystems: Software, Electronics, and Mechanical. The architecture shows the flow of data and energy, in addition to which electronic components contain which software process. First, figure 5 shows the energy flow in the Quadcopter. As shown, there are four different types of power flowing in the Quadcopter. The main power is supplied by the Quadcopter's battery (22.2V). This power is pulled down to 5V using a Battery Eliminator Circuit (BEC) to power the

Odroid. The Odroid in turn provides power via USB to the Wi-Fi module. Lastly, the Guidance sensors are powered internally by the Guidance package.

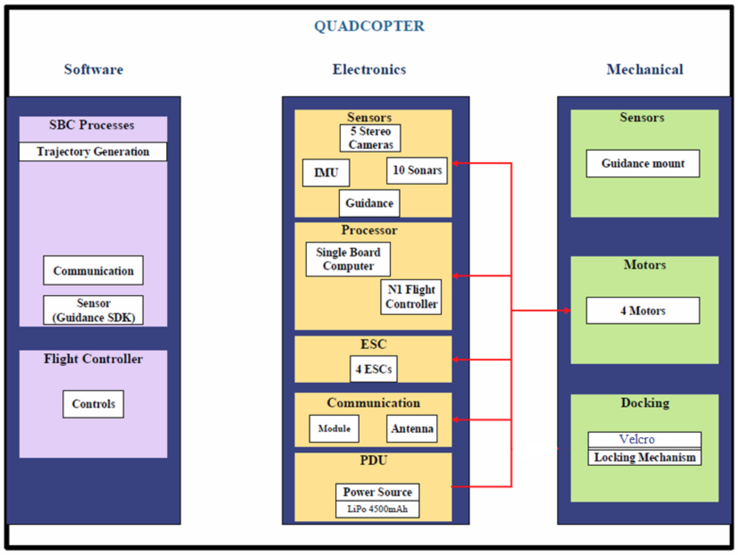


Figure 5 Energy Flow Cyberphysical Architecture of Quadcopter

Second, figure 6 provides the data flow within the Quadcopter. The guidance internally communicates with the IMU, stereo cameras, and sonars and fuses them to provide information over USB to the Odroid. The Guidance also communicates, internally, with the N1 flight control, making the flight more stable in a GPS degraded environment. Since images aren't transferred to the N1, the communication is done through UART. On the other hand, the communication with the Odroid occurs over USB to gain more bandwidth. The Odroid communicates with the user via the wireless module, using a USB link to the module. Lastly, the motors are controlled via ESCs, which are controlled by the N1 flight controller.

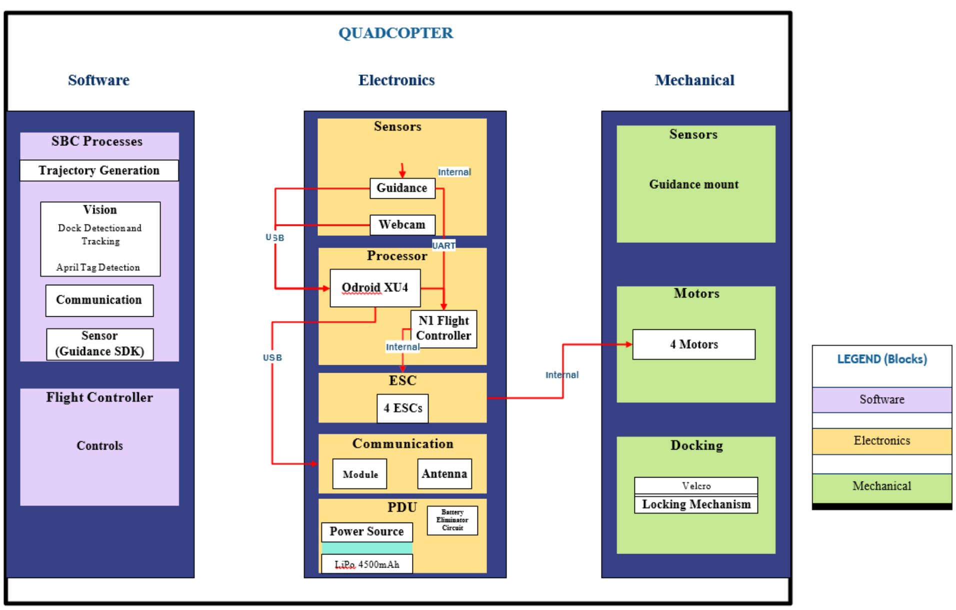


Figure 6 Data Flow Cyberphysical Architecture of the Quadcopter

Last, figure 7 shows the electronic components that contains each of the two software processes. There are two software processes running on the Quadcopter. One to provide low level controls for the Quadcopter's motion. This process is run on the N1 flight controller. Another process provides the higher level functions such as stabilization under the platform. These processes are running on the Odroid XU4. Lastly, the guidance uses sensor fusion on the IMU, stereo camera pairs, and the sonars to provide different outputs. This code is run on the Guidance's internal computer.

The code architecture for the Quadcopter is depicted in figure 8. The guidance SDK instantiates the Guidance parser node, which in turn takes the serial information from the USB bus and publishes topics with the relevant information. DJI's onboard device SDK instantiates the N1 parser node, which takes serial information from the N1 Flight controller and publishes the appropriate topics. The N1 parser node also acts as the middleman to talk to the N1 by providing a set of services and action servers. Using these services and actions, the navigation node navigates the quad through preplanned motions. Lastly, all the data published as topics are logged into rosbags using the Logger node.

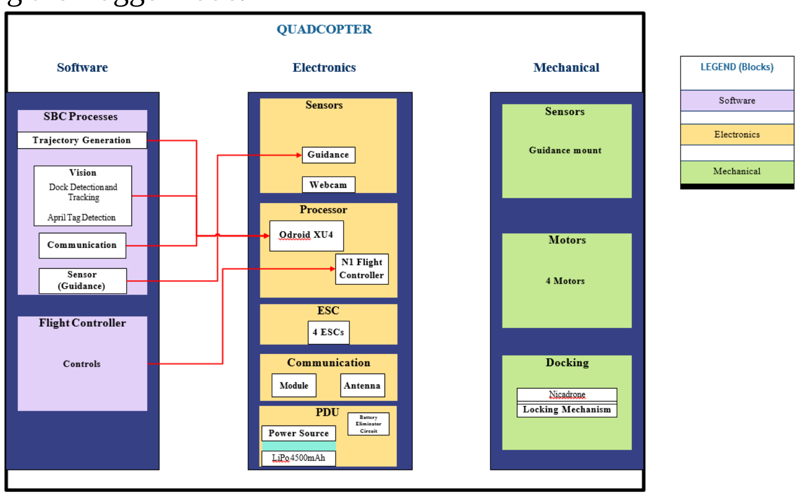


Figure 7 Code Flow Cyberphysical Architecture of Quadcopter

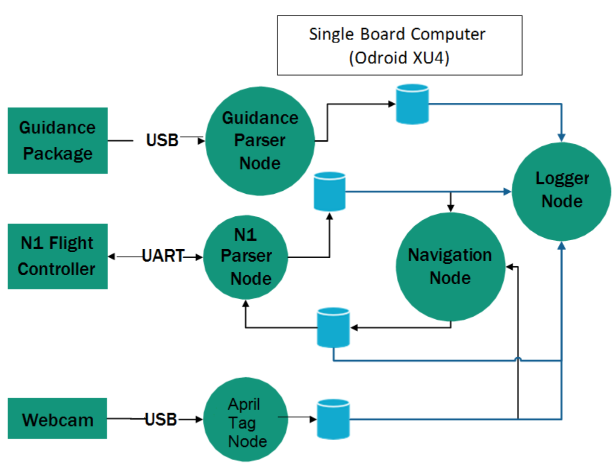


Figure 8 Code Architecture Quadcopter

8 System Description and Evaluation

8.1 System/subsystem descriptions/depictions

The overall system consists of three major subsystems as shown in Figure 9 below.

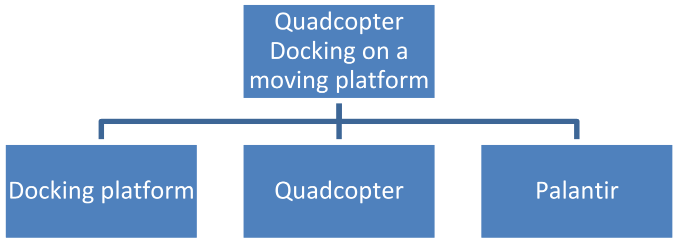


Figure 9 Major Subsystems of the overall system

8.1.1 Docking Platform

The docking platform can be divided into three major sub-systems as shown in figure 10.

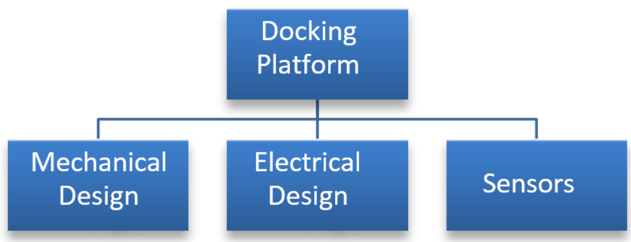


Figure 10 Sub-system components of docking platform

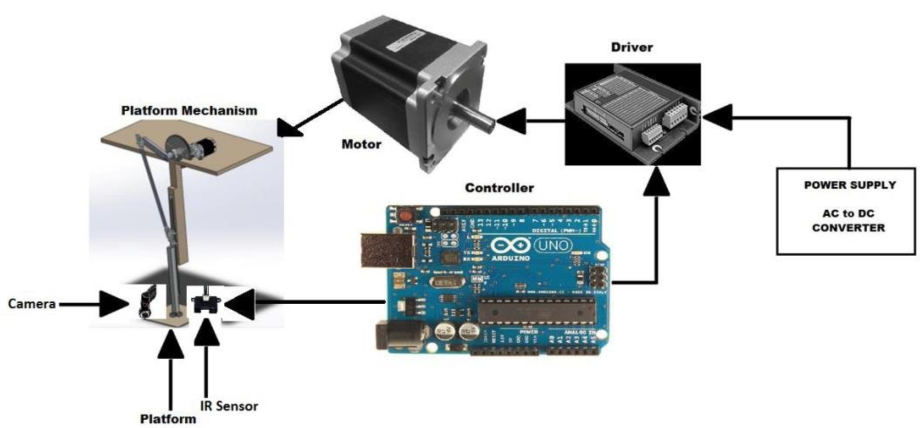


Figure 11 Overall component layout of Docking Platform

Figure 12 Docking Platform

The mechanical design is a slider crank mechanism and the platform is connected to the slider. As the crank rotates the slider moves up and down, causing the desired harmonic motion of the platform. A stepper motor is coupled with the crank and can create rotation at different speeds. Based on our performance requirements, the frequency of up-down motion of the platform can vary between 0.15 to 0.23 Hz (Scaled down due motor torque issues). This variation is obtained by changing the control input to the stepper motor controller using an Arduino Uno. The various parts of the system are shown in figure 11. The actual platform is shown in figure 12 and the gear train and the stepper motor is shown in figure 13.

The motion of the platform is sensed using an Infrared Sensor (IR). The waveform obtained from the motion (shown in figure 14) is used to find the frequency of the platform motion. This information is subsequently provided to the quadcopter to determine the right instant to dock.

Figure 14 Gear train and stepper motor [7] of docking platform

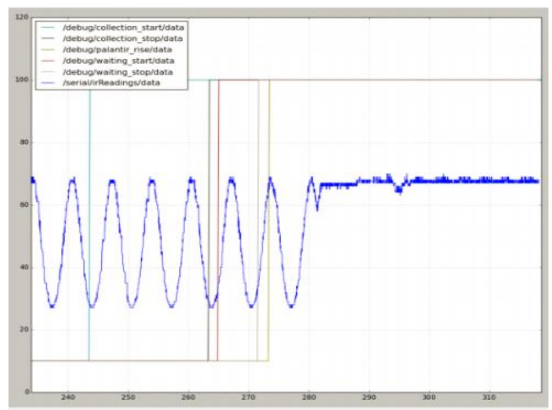


Figure 13 Real time plot of IR data used to estimate the motion of the platform

The IR values are read in real time through a serial port using a serial read node written in Python. The waveform obtained are shown in the figure below along with the prediction times which will be explained in detail in the Palantir subsystem. The dock is suspended on a superstructure hung from the ceiling of the laboratory space in NSH (Newell-Simon Hall) level B. The platform's locking mechanism is a pad of Velcro glued to the bottom of the platform (Figure 15) and its counterpart glued on top of the quadcopter. Four IR sensors monitor the space just below the platform to see when the quadcopter docks and to generate a trigger to record the time at which docking

Figure 15 Dock hanging from ceiling with IR sensors, camera, and locking mechanism

occurs, making it possible to calculate the dock's and quadcopter's velocity. These values are used to find the relative velocity between the platform and the quadcopter at the docking instant which is required to confirm our functional requirement of docking without collision. If the relative velocity at the docking instant is less than 0.5 m/s then it classified as a successful dock without collision. A camera (also visible in figure 15), looks down at an April Tag on the quadcopter which forms the vision system and is used for X-Y stabilization of the quadcopter below the platform. It is also used to maintain a safe distance between the quadcopter and the minimum point in platform motion by using the Z values from the April Tag detections.

8.1.2 Quadcopter

The quadcopter sub-system includes the DJI Matrice 100 [4] with the Guidance and a locking mechanism as shown in figure 10(a). The Guidance[5] as shown in figure 10(b) provides the N1 flight controller more stable velocities using optical flow. The N1 Flight controller runs low level control algorithms, while the single board computer (Odroid XU4) runs higher level processes to control the quadcopter as per our requirement. Power supply to the Odroid is provided through a Castle 5V, 10 A Battery Eliminator Circuit (BEC) as shown in the figure 10(c).

(a) (b) (c)

Figure 16 (a) DJI Matrice with Velcro and AprilTag, (b) Guidance Sensor Package (c) Battery Eliminator Circuit (BEC)

8.1.3 Palantir

Palantir subsystem is used to fine the optimum moment to dock on the moving platform by using data from the IR sensors which track the motion of the platform. To do so the IR data is collected for 1000 data points (for 20 seconds at 50 Hz) through a serial read in Python. The mean of this data is calculated and the values are normalized using it. Thereafter, Fast Fourier Transform (FFT) is performed on the data to determine the dominant frequency of the data. As seen in the figure 17 below the FFT response has many other frequencies due to noise. Thus the dominant frequency obtained is not always accurate. To account for these differences we took frequencies in the range of +/-10% of the dominant frequency, at steps of 1% of Dominant frequency and tried to fit a curve using non-linear regression using the following equation.

$$y = B_0 + B_1 \sin \omega t + B_2 \cos \omega t$$

To find the best values of B_0, B_1, B_2 and ω we minimize the S.S.E (Sum of Squared Errors) between the y (predicted) and y (actual).

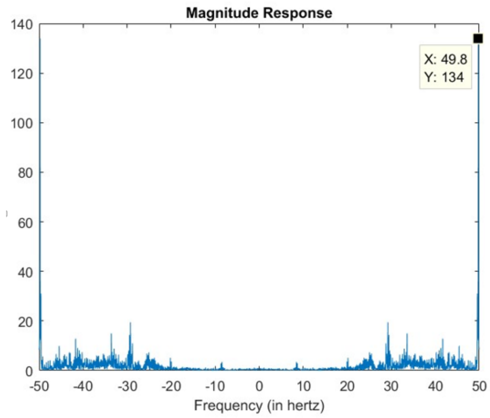


Figure 17 FFT plot of 0.2 Hz

Once the function is determined we extrapolate and find the crest of the waveform after one cycle. One cycle is skipped to ensure that the quadcopter gets sufficient time to move and approach the platform. The time to move is calculated by subtracting the processing time taken for the above computations and 1/8th of the cycle to ensure that the quadcopter begins to move at the lowest point and docks at of before the platform reaches the mean point in its motion.

The final code distribution is shown in figure 18 below. The vision node is run on the laptop to obtain faster processing rates. Only the required nodes are run on the ORDROID to avoid latency issues. The Palantir Node and the Decision node form the communication system between the laptop and the ODROID. The time to move and the velocity to move is given by the Palantir which is received by the Decision node. The Decision node estimates the time left and then counts down till the time to move and publishes the velocity to move at that instant. This value is read by the Navigation node which commands the quadcopter to move up.

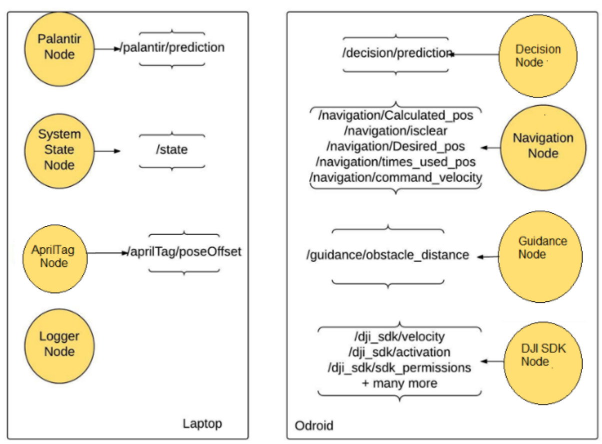


Figure 18 Code structure

Figure 19 shows the state machine implementation and the flow of control from one state to another during complete process of docking on a moving platform.

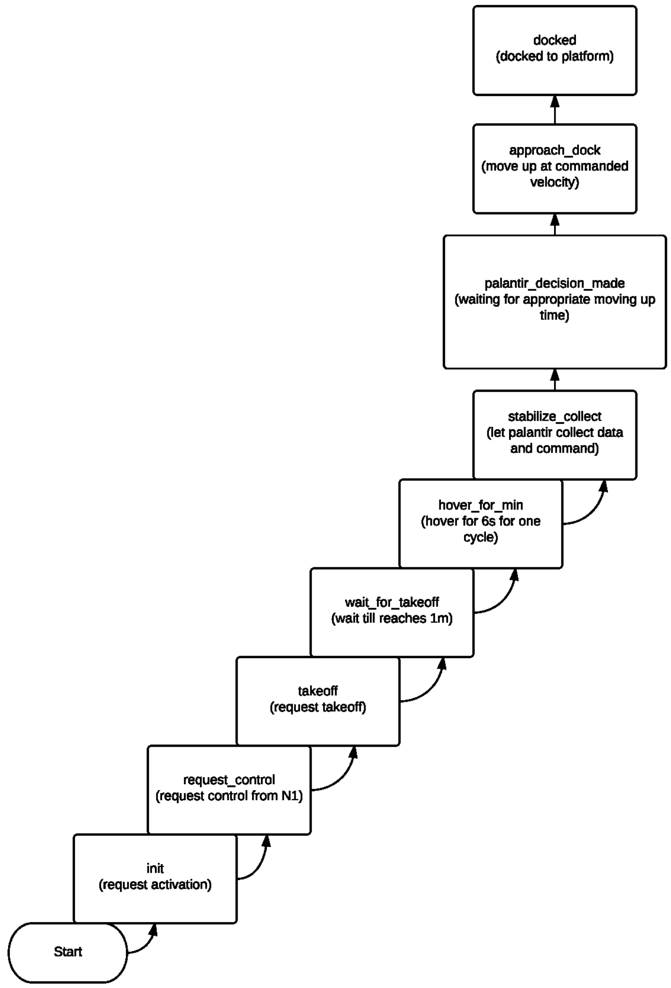


Figure 19 States showing change between different states of the state machine

Our physical system is an approximation of the actual motion of the TMS. In reality the motion is much more random. To show the strength and portability of our prediction system we implemented the logic in MATLAB and tested it on the actual data of TMS motion provided by M/s FMC Technologies Schilling Robotics. The only modification made was that instead of storing 1000 data points, values were stored from the peak of the waveform to 6 points beyond the mean. This is done because unlike our sinusoidal system each cycle was independent of each other. The figure 20 below shows the prediction made by this system. There was a confidence measure incorporated to give an estimate of how sure the system is about its prediction. This confidence depends on the number of data points collected. The error metric was determined based on the difference in the time and velocity at the mean value between the prediction and the ground truth.

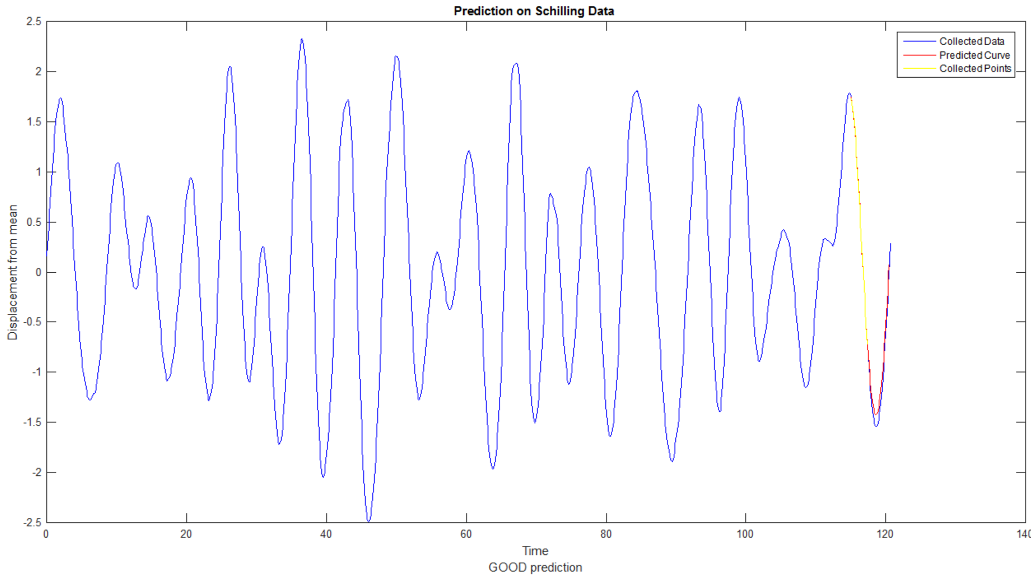


Figure 20 Example of good prediction on Schilling Data

8.2 Modelling, Analysis and Testing

8.2.1 Docking Platform

The docking subsystem is the testing apparatus in our project that emulates the Tether Management System's up and down motion (heave) which is caused due to the waves and the spring like nature of the tether resulting in a harmonic motion. To accomplish this project's mandatory requirement, we will be docking on a moving platform with a single harmonic.

Overall the docking platform consisted of 3 major areas of work –

- Mechanical
- Motor
- Sensors

The mechanical section consisted of the design, modeling and fabrication of the dock. Once the trade studies between various possible dock designs were done, component selection and final design went hand in hand towards the final dock design. To reach to the final dock design various designs for possible docking platforms were prototyped.

The three designs that were considered were

- Rack and Pinion

This design included a platform connected to a rack and a pinion gear attached to a direct current motor. (Figure 21) This was rejected due to its complexity, both in design and its control as it reduced the reliability of the mechanism.

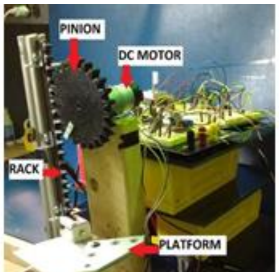


Figure 21 Rack and Pinion

- Ball Screw

In this design we attached a ball screw to a cantilevered platform. (Figure 22) Even though the design handled the load well without many deflections, it was rejected due to the high power required by the motor to drive it. It was around this time that we realized that our quadcopter drifted quite a bit and that having anything closer to it would be too dangerous. All future designs, therefore, had nothing under the platform.

Figure 22 Ball screw

- Geared crank slider -

This design was rejected initially since it couldn't take a mixture of frequencies or variation in amplitude. However, revisiting our mandatory requirements we saw the need of only one frequency at a time to fulfil it and a 3D printed prototype was built to test its feasibility. The sinusoidal motion was mechanically present because of the design and hence the control was easy with just velocity inputs being given.

Figure 23 Geared Crank Slider

Between a DC motor, Servo motor, and stepper motor we rejected the dc motor because of its complexity in control and the chose the stepper motor over servo motor because it had better holding torque. Servo motors were more expensive for the same amount of torque they provided, and a stepper motor was chosen.

For the final design, the CAD model was made on SolidWorks, considering every manufacturing aspect and parts from McMaster-Carr were selected. (Figure 23) While performing the calculations, to keep a safety margin the whole mechanical and electrical system was oversized by a factor of 2. So instead of 5kg, all calculations were done for 10kg.

This was done in 3 stages:

- Testing the motor without any mechanical appendages.
  - This was to get the basic motor control logic working right.
- Testing with the gear train (but no load)
  - This was to ensure that the gear reduction and other tweaks due to an added gear train were right.
- Testing with the entire platform setup.
  - This was to fine tune the motor control to account for slip because of the weight of the platform

To make the project as analogous to the real problem as possible, we chose an IR sensor to find the frequency of oscillation. While the manufacturing of the actual platform was in progress, the 3D printed prototype was used to get the sensor readings right and were verified using a stopwatch.

Once these 3 components were integrated we found out that there was an error of ± 0.1Hz in every reading that we got. We also performed a load test on the platform and the platform could withstand loads up to 11.40 lbs and broke down at 13.2lbs. Both these numbers were more than our quadcopter's maximum possible weight (7.5 lbs). An important thing to note is that oversizing by a factor of 2 worked perfectly for us as the system was design for 22lbs and could withstand 11.4lbs only, just like we had anticipated.

For locking mechanism the following designs were considered and based on the pros and cons after testing, the Velcro was finalized.

Table 4 Locking mechanism selection

SNo.	Proposed design	Pros	Cons
1	Stick and ball	Withstands weight, tolerance to position errors	The AprilTag is occluded from the stick
2	Nicadrone (Electro-permanent magnet)	Tolerance to position errors, no occlusion of AprilTag	Need to keep the magnet attached to the metal sheet for 1.25 seconds during magnetization to withstand weight. Difficult to achieve due to the disturbances in quadcopter motion
3	Permanent magnets	Withstands weight, tolerance to position errors, no occlusion of AprilTag	Magnetic fields interfered with the compass of the quadcopter causing it to drift significantly
4	Velcro	Withstands weight, tolerance to position errors, no occlusion of AprilTag	Adhesion weak if the quadcopter docks on the sides of the platform

8.2.2 Quadcopter

Quadcopter has two major sub-systems the AprilTag Detection and Motion. The development was tested using unit tests depicted in figure 24. The final result of the development was the AprilTag node publishing the deviation of the tag and hence the quadcopter from the center of the platform in the X-Y plane. It also gives the distance along Z-axis which is used to maintain safe distance from the platform. The individual steps for the development procedure of quadcopter are shown in figure 24 below

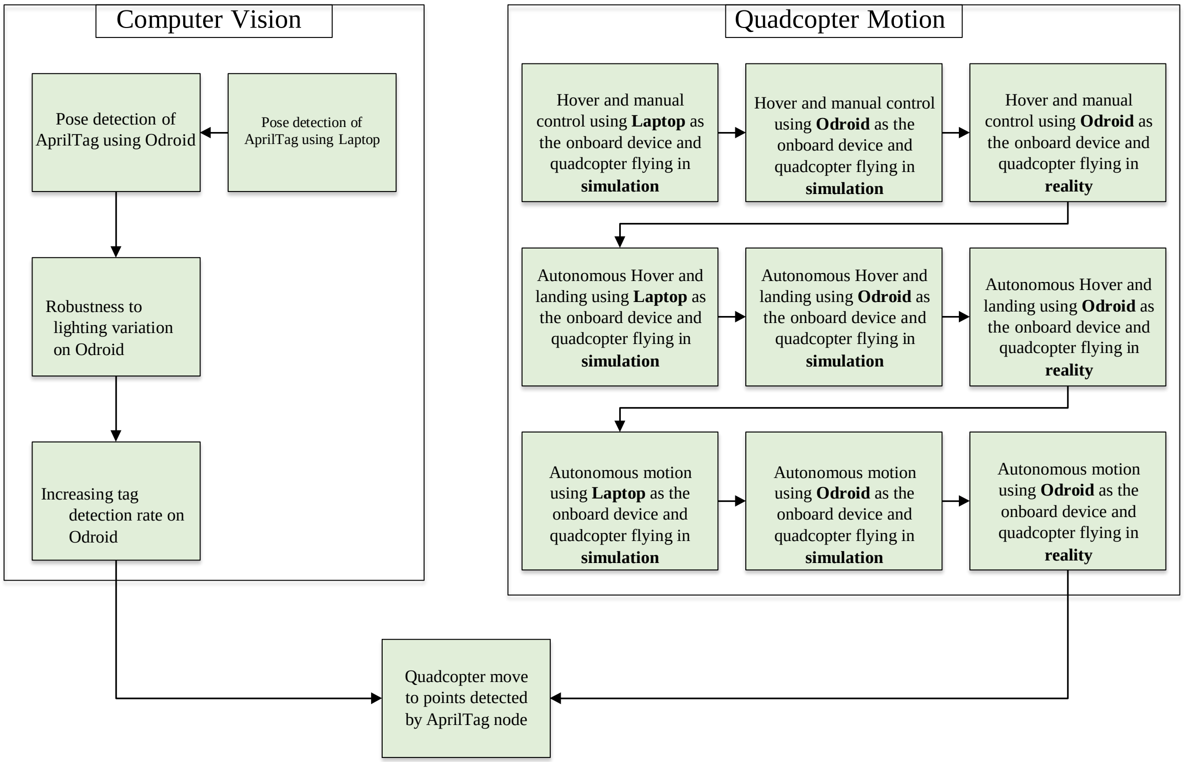


Figure 24 Development Procedure for the Quadcopter

Quadcopter motion was tested using the set-up detailed in figure 25. When the quadcopter is run on the simulation the drone is connected via a USB cable to the laptop running the simulation. Whatever commands are provided to N1 are sent to the simulation internally and used to run the drone in the simulation. Additionally, the Remote Controller is present for emergency takeover. However, the mode is set to 'F' when Odroid needs to be in control. The mode needs to be changed to 'A' when manual override needs to be activated. The code is run by opening a secure shell from a laptop. Data from all the topics are logged using rosbag.

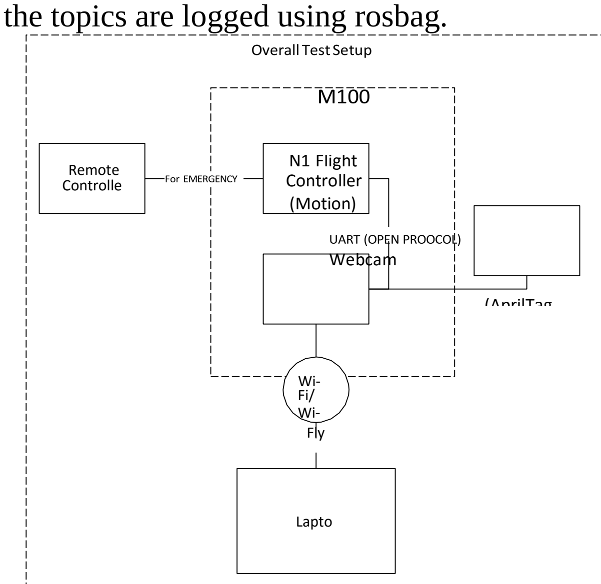


Figure 25 Test Set-up for Quadcopter Testing

Analysis was performed on the logged data. For example, the velocity controller on the quadcopter needed to be validated before implementing a position controller. To do this, the quadcopter was flown using the velocity controller in simulator, and figure 26 depicts the logged velocity data. Note, positive Z is pointing down, making the initial negative velocity the liftoff and the final positive z-velocity the landing. A sequence of velocity commands in the x and y axes were provided with a magnitude of 2 m/s. This graph validated our use of the velocity control service exposed by the N1 parser node.

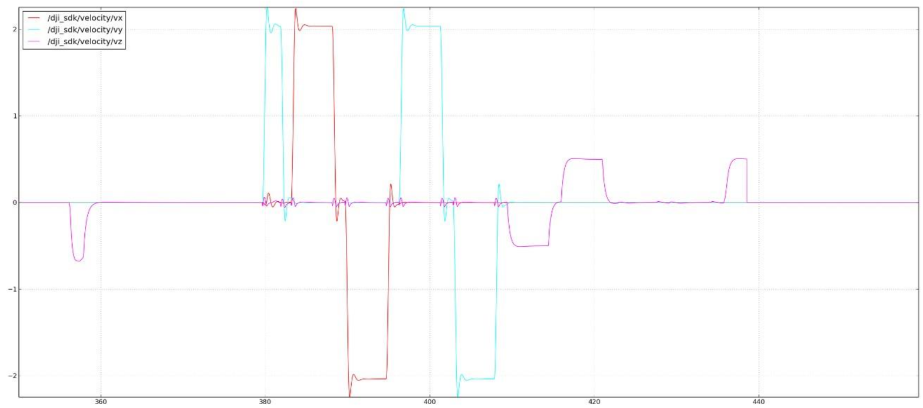


Figure 26 Velocity Test Data from Simulation flight

A more interesting show of our analysis is provided by the figure 27. This figure is taken when the quadcopter was in flight, not in simulation. The graph shows the huge spike in the z-axis velocity in the positive direction, which is consistent with a fall. This graph is the result of giving a position offset of 1m in both x and y direction. The main take-away from this graph is that changing the local navigation action exposed by the N1 parser node is troublesome as there are dependencies that aren't clear. The local navigation action is the actionlib instance that takes the quadcopter to a requested destination.

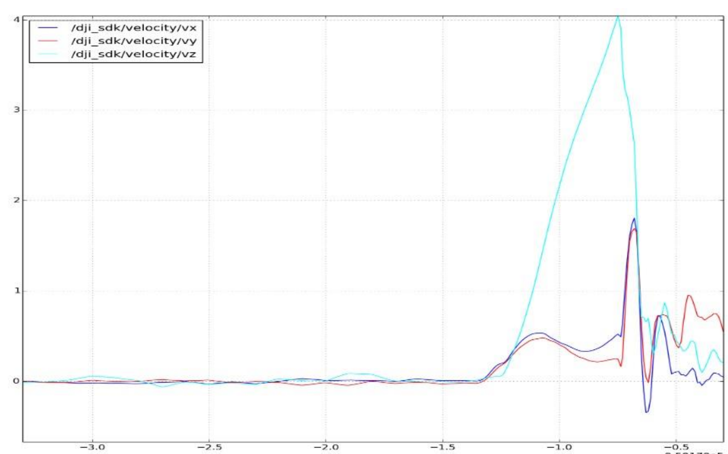


Figure 27 Velocity Data from the Crash

8.2.3 Palantir

While developing the Palantir subsystem testing and evaluation was done using a range of frequencies before implementing it on the quadcopter. Figure 28 below shows the various times which were analyzed to ensure that the quadcopter docks at the desired time instant. Starting from left the first line indicates the time at which the data collection begins, the second line indicates the end of data collection, the third line indicates when the palantir makes the decision, the fourth line indicates the time at which the docking should take place and the last line is the actual prediction made by the palantir. This offset in the desired and predicted is due the processing time taken by the palantir. Using this analysis method we were able to account for this latency and provide the correct time to move to the quadcopter.

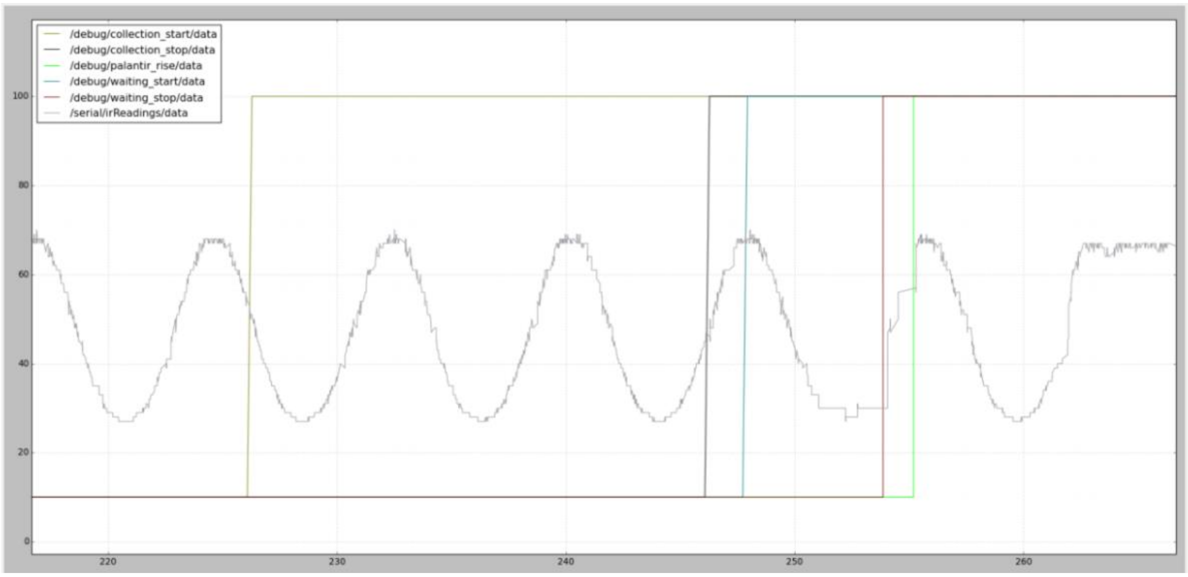


Figure 28 Plot of IR data with prediction

8.3 Performance evaluation against the Spring Validation Experiment (SVE)

Table 5 highlights the key objectives of the SVE and our performance. As it can be seen we were able to achieve all of our goals, however reliability of the system docking on the first attempt was only achieved outside of the experimental time period, with testing showing a much higher reliability than was demonstrated. The cause of this is believed to be linked to the Guidance subsystem, which is highly sensitive to motion in the testing area. During validation testing, our success rate was 90%, during the lab tours it was 85%, and in SVE it was 67%. This indicates that the system degradation is linked both to quantity of noise in any given direction and how many directions the noise was coming from. The highest reliability came when only one quadrant had moderate noise (operators in operation space), followed by high noise in one quadrant and moderate in a second (tour group in tour space and operators in operator space), and finally lowest values were found with high noise in one quadrant and moderate noise in two others (evaluators in tour space, operators in operator space, evaluators near the lab exit door). This makes sense, as the Matrice's expected operating space is well above most objects, meaning that the majority of what it perceives is expected to be static obstacles like poles and buildings. Operating low to the ground with many people moving in its view, the Guidance was put in a state of uncertainty about objects in its environment. As a result the system shifted to IMUs estimates which have significant error causing the quadcopter to drift.

Table 5 Performance against SVE targets

Requirements	Expectations	SVE	SVE-ENCORE
MP1.1, MP1.2, MP1.3	Docking platform shall move according to the given input frequency in Z-direction	Successful Dock changed to given frequency as detected by IR	Successful
MP1.4	Docking platform shall have a locking mechanism which supports weight of 5 kg	Successful Dock held quadcopter for 30 seconds without external support	Successful
MP1.2	Sensor gathers data from the motion of the platform and outputs the frequency within an accuracy of 0.05 Hz	Successful	Successful
MP2.1	Quadcopter shall localize w.r.t. platform within 50mm accuracy	Successful Quadcopter maintained XY centered hover with a distance of less than 50mm between center of quadcopter and center of platform	Successful
MP2.2	Quadcopter shall dock to the platform autonomously and without colliding within 10 minutes	Successful Quadcopter docked 4 times and rejected once, with an average relative velocity of 38 cm/s and an average time of 1.5 mins	Successful
MP2.2	Quadcopter shall dock to the platform autonomously and without colliding in 80% of tests	Not Successful Quadcopter docked 4 times and rejected once out of 6 attempts, a rate of 67% However, exhaustive testing outside of demo showed a failure rate of 3 out of 30, 90%	Not Successful
DP2.1	Quadcopter shall localize w.r.t. platform within 30mm accuracy	Successful	Sucessful
DP2.2.	Quadcopter shall dock to the platform within 5 minutes	Successful Docking occurred in an average of 1.5 mins	Successful

8.4 Strong/Weak Points

The key strengths and weakness of our developed sub-systems are listed in table 6.

Table 6 Strong and weak points of our system

STRENGTHS	WEAKNESSES
Docking platform is robust	Velocity control not stable in Matrice 100
Motor is powerful	Flight controller code is not accessible
April Tag works suitably even in low lighting	Cannot provide state estimation values to flight controller
IR is giving accurate readings	Matrice 100 often switches out of Guidance mode, especially when there is significant motion in the background
Indoor hovering is stable using guidance	

The motor and platform are strong enough to withstand the weight of the quadcopter after it has docked. A 100% margin was used while selecting the motor. Currently, it can withstand weight of 5 kg at 60V and the maximum take-off weight of the quadcopter is 3.4 kg. Higher torques can be achieved at higher voltages. The accuracy of IR readings was critical to our project because these values will be transmitted to the quadcopter and used to determine the suitable moment to initiate the docking operation. The April Tag detection is working suitably in low light conditions as well as when the resolution is reduced to one-fourth of the original resolution. Also, the tag detection rate is 20 Hz in poor lighting conditions. We are able to achieve stable hover of quadcopter indoors using the Guidance. However, with significant motion in the background, it often requires multiple resets.

Another weakness is that the flight controller's code is not accessible to us and we cannot provide state estimation values to it. Thus, the only possible option to do position control is to provide velocity commands. The loop is closed using information provided from the IMU sensors and the Guidance's cameras. The IMU does not provide accurate position estimates due to high noise. The Guidance uses optical flow to calculate velocity. This is effective only if there are significant non-repeating features available for tracking.

There is a need to make the system more robust. Since the switching from Guidance to IMU mode is not in our control we should have incorporated backup control from example the quadcopter should move back and forth till the time it comes in view of the camera. Once it is in the view of the camera it stabilizes using the AprilTag.

9 Project Management

9.1 Schedule

Our schedule was integrated with our progress review (PR) goals, each subsystem we implemented or unit we intend to test being a demonstration at the PR (Table 7).

Table 7 Schedule

Timeline	Progress Review	Planned Milestone	Actual Milestone	Presenter
Late January	PR 7	• Quadcopter motion from Point A to B, Preliminary • Palantir Functionality – Fitting and Communication	• Quadcopter motion from Point A to B, Preliminary • Palantir Functionality – Fitting and Communication	Paul Calhoun
Mid-February	PR 8	• Determine position and velocity of platform using CV and sensors • Quadcopter maintains hover point in XY Plane	• Determine position and velocity of platform using CV and sensors • Quadcopter maintains hover point in XY Plane	Bishwamoy Sinha Roy
Late February	PR 9	• Stabilization of Quadcopter under the Platform • Docking to the platform with the Nicadrone	• Stabilization of Quadcopter under the Platform	Keerthana Subramanian Manivannan
Mid-March	PR 10	• Achieve docking on moving platform	• Quadcopter hovers at a fixed point below platform • Palantir outputs correct curve fit to Dock Data	Aishanou Osha Rait
Early April	PR 11	• Testing and refinement • All dock motions produce correct outputs – Docks or refuses to dock	• Quadcopter docks to stationary platform • Dock detects successful docking action	Rushat Gupta Chadha
Mid-April	PR 12	• Testing and refinement • Quadcopter lands within time limits and with 80% success rate	• Achieve docking on moving platform • All dock motions produce correct outputs: – Docks or refuses to dock	Paul Calhoun

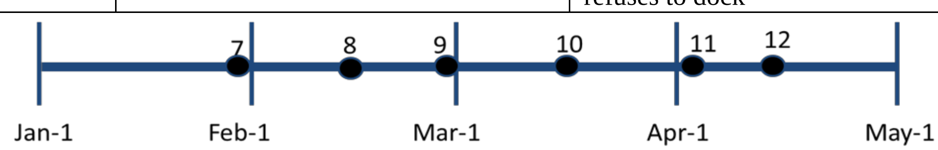


Figure 29 Timeline

We followed the timeline (Figure 29), quite well, with only the locking mechanism going more than a week past due, and causing a minor slip cascade that persisted until PR 11 in early April. This was because our original plan of using an Electro Permanent magnet (EPM) proved unworkable due to the EPM requiring 1.25 seconds' contact with the dock to function. Our attempt to use permanent magnets also failed when it interfered with the navigation of the Quadcopter, making the compass cease functioning. The locking mechanism was a key item to several other developments, which had to be put on hold until the team found an acceptable replacement for the EPM.

9.2 Budget

Table 8 Refined Parts List

Item	Cost	Type	Funding Source	Comment
DJI Matrice 100	$3,299.00	Capital	Sponsor	Developer Quadcopter
DJI Guidance	$999.00	Capital	Sponsor	Sensor suite and collision avoidance for Quadcopter
Guidance Connector Kit	$79.00	Consumable	Sponsor	Connectors for Guidance
TB48D Battery	$199.00	Capital	Sponsor	Extra Battery
Quadcopter Spares	$450.00	Consumable	Sponsor	Spare Legs and Props for Quadcopter
Physical Dock Components	$ 1186.13	Consumable	CMU	Components used to construct dock
Quad Electronics	$591.55	Consumable	CMU	Electronics mounted on Quadcopter
Dock Electronics	$393.87	Consumable	CMU	Electronics that were mounted on dock
Quadcopter Spares	$885.50	Consumable	CMU	Spare Legs and Props for Quadcopter

Our sponsor contributed $5000 of equipment to our project, and we used that to purchase our big ticket items – the Quadcopter and the Guidance along with spares which comprise the majority of the budget (Table 8), see Appendix A for a full listing of our parts and purchases. Our $4000 from the MRSD program was used to buy many small items which were combined into larger subsystem components like the dock structure and the motor control architecture, as well as the dock superstructure.

Our sponsor budget is almost exhausted, being approximately 95% executed. This was almost all done at the very beginning of the Spring Semester so we could purchase our Quadcopter and the necessary components for it. Our CMU budget is approximately 96% executed. (Table 9)

Table 9 Budget Summary

CMU total budget	$4,000.00	Sponsor total budget	$5,000.00
Total Executed from CMU	$3835.44	Total Executed from sponsor	$4,726.00
CMU budget remaining	$164.56	Sponsor budget remaining	$74.00

The budget was for the most part smoothly executed, with only $632.02 of it being executed on purchases made through reimbursement rather than through the MRSD approved purchasing process. Out of that, $406.58 was for the dock superstructure, purchased from Home Depot. This was an unavoidable situation. The rest were for electronic components that needed to be replaced quickly, and $187.95 for a PCB mistakenly purchased because the team member in charge of that subsystem had a mistaken belief about how PCB purchases were made. In the first semester one team member took care of purchases and budget, and in the second semester it was consolidated into the overall PM tasking. This was done as PM tasking also included coordination, which helped in keeping track of who needed what and why.

9.3 Risk Management

Table 10 Risk Summary

Probability	Severity	A Negligible	B Low	C Moderate	D Severe	E Catastrophic
5	Nearly Certain	0	0	0	0	0
4	Likely	0	0	1	0	0
3	Possible	0	0	0	0	1
2	Unlikely	0	0	2	2	1
1	Rare	0	1	0	1	0

Immediate Action	Urgent Action	Action	Monitor	No Action

Team Dock-In-Piece has had a successful risk mitigation strategy. (Table 10)

By the end, we had mitigated all the highest level risks and most of the middle risks. The remaining risks are distributed evenly from the physical (dock motor not working right) to the supply chain (spares strategy insufficient) to the human resource (a developer becomes unavailable). See Appendix A for a full listing of our risks. Risk ID 5, 6 7, 19, 23, 24, and 25 involve direct physical risks to the Quadcopter. Each failure mode is captured as a separate risk, as most of them require different methods of being mitigated and prevented – all but one of which was fully mitigated by the end either by scope changes or our risk strategy.

During the former part of the academic year, we had faced a lot of delays in shipping, which led the team on a late start of the project. But, the team had successfully completed the FVE nonetheless. The team decided to work on the Quadcopter's software during the winter break, which gave us time to test and refine the process early.

In the Spring semester, we had faced significant delays as well. Some of them are: finalizing the locking mechanism, finding a place for testing, Guidance failing mid-flight.

The locking mechanism had an unexpected delay as we brainstormed for and tried on different methods. This was mitigated by using a simple solution to a problem – using Velcro as the locking mechanism.

The team faced shortage of spare propellers before one of our PRs. It was then mitigated by ordering a large number of spare propellers and spare arms for the next PR. During one of our testing, the Quadcopter fell and a part on the arm was broken, and it is one which cannot be bought off the internet. So we borrowed the part from another team who were working with M100 on their project to show the goals to be achieved in PR.

The risk chart was constantly updated by the Project Manager and the items were moved to lower portions as they were mitigated.

The team, however, failed to mitigate the problem of motor giving out bad outputs. The motor wouldn't perform as it was expected since it didn't output the input frequency. The problem of Guidance failing mid-flight is also not resolved. The final system sometimes fails because the Quadcopter drifts off since the Guidance doesn't work.

One method of mitigating this problem from arising would have been to more thoroughly research the Guidance and motor choices. Seeking help from peers and experts in the respective fields would have helped us mitigate this problem.

Overall our risk mitigation served its purpose and enabled us to deliver a fully autonomous Quadcopter docking onto a moving platform. However, with a few key changes – such as adding more risk mitigation to our schedule and seeking more advice from experts – our risk management system can be even more robust in the future project scopes.

10 Conclusions

10.1 Lessons Learned

As with many teams, our largest lesson learned is requirement generation and tracking. We originally had many requirements that our customer thought would be useful but they didn't need. By reducing our scope to what our customer absolutely needs, we've streamlined our process and expectations so we can produce a working system. The de-scoping continued through both semesters as we got an even better idea of our customer's intended use, including removing undocking from the requirements and no longer requiring a dedicated user interface.

Our trade studies also did not have logistics and maintenance as columns. While this would have been difficult in many cases, further research may have helped us realize that our main suppliers for vehicle and motor had very long lead times for delivery. In both cases we had to wait over a month for key components during which development in non-key areas. In the Spring, this was mitigated by ordering further in advance, ordering from suppliers that delivered faster, and by not needing as many key components.

Communication was a big problem during sprints. Spring semester's schedule permitted a more structured teaming process so that we don't lose sight of the full system as we implemented subsystems. Our documentation was also not kept up to date during the Fall, producing lengthy catchup periods as we entered large volumes of information into our databases. In the Spring, we at first attempted to have more structure with regular meetings and a single dedicated model in which everything was kept up to date. This eventually gave way to not requiring documentation at all, which streamlined the process significantly as we no longer had the internal customer requirement (course presentations) to keep such records.

We have done very well in the Spring with finding test facilities. Not only did we arrange for and construct the docking superstructure for ourselves, but we also assisted another group in getting space and equipment away from our own, freeing up the space we had to be dedicated to our use only

10.2 Future Work

While our Use Case works hard to productize our system, charting a way forward to use our system as the basis of a startup is somewhat difficult. Perhaps some of our system could be useful for the military's drone swarm system, allowing for the swarms to dock to the outside of a dirigible rather than inside a hangar bay. In that way, they could use solar panels to recharge rather than drawing entirely on the ship's energy store. Unfortunately, ITER restrictions being what they are, only one member of the team would be able to work on sensitive sections of that system, however one benefit is that the relative maneuverability of the drone is much greater, and so prediction based docking is an easier task. In a distant future case, there is the possibility of needing a system like ours if air travel becomes individualized and modular, with swarm-like craft sharing an air stream and small portions dropping off and attaching as the gestalt crosses over the landing areas in each town. While the swarm ship might be able to maneuver to accommodate the new addition, it seems more likely that the swarm's heading would be fixed and the ships detaching and attaching would need to do all the work.

Further work in this project would be to test the Guidance and make the system more robust to the Guidance failures which occur mid-flight. One more area which could be explored is the motion of the platform. Currently the system is designed in such a way that the platform moves only in the z-axis. The platform could be made to move in other directions as well which helps us simulate the sub-sea motion.

11 References

[1] Stepper motor: http://www.lamtechnologies.com/Product.aspx?lng=EN&idp=M1343051

[2] Stepper motor driver: http://www.lamtechnologies.com/Product.aspx?lng=EN&idp=LS1078

[3] IMU: http://playground.arduino.cc/Main/MPU-6050

[4] DJI Matrice 100: https://developer.dji.com/matrice-100/

[5] DJI Guidance: https://developer.dji.com/guidance/

[6] On-Board SDK: https://developer.dji.com/onboard-sdk/features/

[7] Guidance SDK: https://developer.dji.com/guidance-sdk/

MRSD Project – Dock-in-Piece

December 17, 2015

Appendix A

Table 11: Column IDs for the Risk List Table below

Column ID	Name
1	Risk
2	Probability
3	Severity
4	Date Identified
5	Requirement Impacted
6	Consequence
7	Mitigation
8	Risk Type
9	Action to Take

Table 12: Complete List of Risks

ID	Risk	Probability	Severity	Date Identified	Requirement Impacted	Consequence	Mitigation	Risk Type	Action to Take	Action Taken
1	DJI SDK is an unsuitable development platform	0	0	10/2/2015	F2.1-4 , MP2.1-3	Quadcopter subsystems not complete on schedule		Cost	No Action	Exhaustive Testing
2	Matrice cannot support our needs	0	0	10/2/2015	F2.1-4 , MP2.1-3	Need new quadcopter	Research prior to purchase	Cost	No Action	Exhaustive Research
3	Guidance sensors unsuitable to our requirements	0	0	10/2/2015	F2.1-4 , MP2.1-3	Sensor suite has to be made from scratch		Schedule/ cost	No Action	Exhaustive Research
4	Simulations diverge significantly from reality	2	C	10/2/2015	ALL	Schedule delays	Careful simulation creation	Schedule	Monitor	Testing

MRSD Project – Dock-in-Piece

December 17, 2015

5	Docking mechanism fails while Quadcopter is docking or docked	0	0	10/2/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Place net under platform	Physical	No Action	Strengthening and testing of docking mechanism
6	Quadcopter collision avoidance fails in flight	1	D	10/2/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Keep Guidance On	Physical	Monitor	Careful unit tests
7	Quadcopter attempts to shut down engines after a false positive dock	0	0	10/2/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Place net under platform	Physical	No Action	
8	Delays in shipping	4	C	10/2/2015	ALL	Subsystems lack parts to be complete	Order in advance	Schedule	Action	
9	NSH lab not big enough for testing	0	D	10/2/2015	ALL	Delays as we find somewhere else	Find that out early and reserve Rangos	Schedule	No Action	Helped get other team space elsewhere
10	Electrical failures	2	C	10/2/2015	ALL	Possible damage to subsystems, delays in repair	Wire safety / fuses	Schedule/ cost	Monitor	
11	Platform fails mechanical requirements	0	0		F.12, MP 1.4	Delay while dock is rebuilt	Make another one	Schedule	No Action	Careful design
12	Navigation algorithm more difficult than planned	0	0	10/19/2015	F2.1-4 , MP2.1-3	Quadcopter navigation subsystem not completed on schedule	Keep in contact with other CMU developers	Schedule	No Action	
13	A developer becomes unavailable	3	E		ALL	Cannot satisfy key requirements		Schedule	Urgent Action	Culture of safety
14	Indoor flight impossible	0	0	10/22/2015	F2.1-4 , MP2.1-3	Cannot satisfy key requirements		Schedule	No Action	Research

Carnegie Mellon
THE ROBOTICS INSTITUTE

MRSD Project – Dock-in-Piece

December 17, 2015

15	SDK Legal Issues Continue for significant time	0	0	10/22/2015	F2.1-4 , MP2.1-3	Quadcopter subsystems not complete on schedule	Get a personal license	Schedule	No Action	Research
16	Motor has insufficient torque	0	0	10/22/2015	F1.1-2, MP1.1-4	Delay while new motor is found	Learn more about motors	Cost/Schedule	No Action	Research
17	Quadcopter Fails to Arrive in time for FVE	0	0	10/29/2015	F2.1-4 , MP2.1-3	Demo cannot be completed	Lower expectations	Schedule, Programmatic	No Action	
18	Hover/manual control dependent on netgear wifi module	0	0	11/16/2015	F2.1-4 , MP2.1-3	Quadcopter testing delayed	Scope down into laying April tags in descending order to mitigate drift	Schedule, Programmatic	No Action	
19	Quadcopter Spares Strategy Insufficient	2	D	12/13/2015	F2.1-4 , MP2.1-3	Quadcopter testing delayed	Failure Mode Effects and Criticality Analysis	Schedule	Action	Spares strategy re-evaluated periodically
20	Motor burns out	2	E	12/13/2015	F1.1-2, MP1.1-4	Delay while new motor is found	Overcurrent Fuse	Cost, Schedule	Action	
21	Dock Strikes Pantrybot Frame	0	B	12/13/2015	F1.1-2, MP1.1-4	Delay while dock is rebuilt, loss of goodwill if we damage the Pantrybot	Temporarily Remove Letters from Pantrybot	Cost, Schedule	No Action	Move to a separate location
22	Arduino Not Fast Enough to Control Motor	1	B	12/13/2015	MP 1.2	Dock subsystem will require redesign	User Datagram Protocol Edits to the Driver Setting	Schedule	No Action	Update motor driver settings
23	Quadcopter Lands Upside Down (operator influence)	2	D	12/13/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Soft Landing Platform	Cost, Schedule	Action	Careful testing

24	Guidance Fails Midflight	0	0	12/13/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Switch to Manual Control Faster	Cost, Schedule	No Action	Careful testing
25	Quadcopter propulsion does not disengage after docking	0	0	12/14/2015	F2.1-4 , MP2.1-3	Damage to quadcopter	Limit switch on quadcopter	Physical	No Action	
26	No place to hang dock	0	E	12/15/2015	ALL	System cannot be tested	Find somewhere to put the dock	Programmatic	No Action	Worked with facilities to build dock superstructure
27	Locking Mechanism Delayed	0	0	2/15/2016	ALL	System cannot be tested	Do not show locked situation	Programmatic	No Action	Analysis of alternatives

MRSD Project – Dock-in-Piece

December 17, 2015

Table 12: Complete Budget

Part Name	Quantity	Unit Price	Total Price	Reconciliation description including: Quantity, Part name, use description, "for MRSD project course" location it will be kept (NSH B504/B506?) and team name and team captain (ORDERS WILL NOT BE MADE UNLESS THIS COLUMN IS COMPLETED)
Accelerometers	2	$9.95	$19.90	Accelerometers to detect movement of platform for MRSD Project Course NSH B506 Team E Keerthana Subramanian Manivannan
Nica Drone Electro Permanent Magnet	2	$52.00	$104.00	Electro Permanent Magnet to help with docking for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
NEMA34 Stepper Motor 9.2Nm	1	$164.00	$164.00	Stepper Motor to control platform motion for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Stepping Motor Driver 90Vdc	1	$189.00	$189.00	Stepping Motor Driver to control Motor for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
ODROID-XU4	1	$74.00	$74.00	SBC for the quad for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
ODROID-XU4 Case	1	$2.70	$2.70	Case to hold the odroid for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
WiFi Module 3	1	$8.00	$8.00	WiFi module for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
DC Plug Cable Assembly 5.5mm L Type	1	$1.25	$1.25	Plug cable for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
USB to TTL Serial Cable	1	$9.95	$9.95	USB to TTL Convertor Cable for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
AC/DC Adaptor Charger Cord	3	$6.99	$20.97	Charger Cord for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
PCB Parts - Mouser Electronics				PCB Parts for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Steel Drive Shaft	2	$24.09	$48.18	Shaft for gear for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
External Retaining Rings	1 pack	$8.25	$8.25	Retaining Rings for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Steel Mounted Ball Bearing	3	$12.69	$38.07	Ball Bearings for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Key Stock	2	$4.53	$9.06	Key Stock for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Flange Mounted Bearing	3	$27.39	$82.17	For platform for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Shaft for Crank	4	$8.30	$33.20	Connecting Rod for MRSD Project Course NSH B605 Team E Keerthana

MRSD Project – Dock-in-Piece

December 17, 2015

				Subramanian Manivannan
Brass Standard Key Stock	1	$1.78	$1.78	Key for end schaft for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Black-Finish Steel External Retaining Ring	1	$10.13	$10.13	Ring for Schaft for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Frelon-Lined Sleeve-Bearing Carriage	1	$41.44	$41.44	Slider Carriage for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Guide Rail, 15mm Wide, for Frelon-Lined Sleeve-Bearing Carriage	1	$93.80	$93.80	Slider Rail for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
McMaster Order	6	$321.71	$321.71	Parts for fabrication of platform for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan
Matrice Landing Gear Kit	1	$19.00	$19.00	Landing gear for the quadcopter for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Mouser Electronics				PCB Parts for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
LiPo Battery	1	$55.61	$55.61	Battery for PCB for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Battery Charger	1	$34.99	$34.99	Battery Charger for PCB for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Linear Regulator	3	$8.04	$24.12	Linear Regulator for PCB for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Wire Harness	3	$10.60	$31.80	Wire Harness for Battery for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Battery	1	$49.73	$49.73	Battery for PCB for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Battery	1	$33.42	$33.42	Battery for PCB for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Matrice Arm M1	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Matrice Arm M2	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Matrice Arm M3	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
Matrice Arm M4	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Keerthana Subramanian Manivannan
WiFi Module 3	1	$8.00	$8.00	WiFi module for MRSD Project Course NSH B605 Team E Keerthana Subramanian Manivannan

Carnegie Mellon THE ROBOTICS INSTITUTE

MRSD Project – Dock-in-Piece

December 17, 2015

FTDI Breakout	1	$14.95	$14.95	FTDI Breakout board for MRSD Project NSH B605 Team E Keerthana Subramanian Manivannan
PlayStation Eye	1	$6.49	$6.49	Monocluar Camera for quadcoper for MRSD Project Course NSH B605 Team E Paul Calhoun
12V Rechargeable Li-ion Battery Pack	2	$9.04	$18.08	Battery Packs for Controllers for MRSD Project Course NSH B605 Team E Paul Calhoun
Arduino Stackable Header Kit	4	$1.50	$6.00	Headers to attach IMU to Arduino for MRSD Project Course NSH B605 Team E Paul Calhoun
DJI 1345s	5	$7.45	$37.25	Spare Propellors for quadcopter for MRSD Project Course B506 Team E Paul Calhoun
Kootek GY-521 MPU-6050	2	$5.99	$11.98	Spare IMU for Dock for MRSD Project Course B506 Team E Paul Calhoun
Linear Regulator	3	$8.04	$24.12	Linear Regulator for PCB for MRSD Project Course B506 Team E Paul Calhoun
Odroid xu4	1	$74.00	$74.00	Odroid to go on quadcopter for MRSD Project Course B506 Team E Paul Calhoun
0.100" (2.54 mm) Breakaway Male Header: 1×40-Pin	5	$0.75	$0.75	Headers to attach boards to Arduino for MRSD Project Course NSH B605 Team E Paul Calhoun
Arduino Nano v3.0	2	$28.99	$57.98	Arduino controller for MRSD Project Course NSH B605 Team E Paul Calhoun
USB 2.0 Extension Cable - A-Male to A-Female - 9.8 Feet (3 Meters)	4	$5.79	$23.16	USB Extension Cables for Data flow MRSD Project Course NSH B605 Team E Paul Calhoun
SW MINI SNAP ACTION .3A VERT 6V	5	$0.78	$3.90	Limit switch for MRSD Project Course NSH B605 Team E Paul Calhoun
SWITCH DETECT SNAPACT SPDT 30V	3	$1.86	$5.58	Limit switch for MRSD Project Course NSH B605 Team E Paul Calhoun
WiFi Module 3	1	$8.00	$8.00	New Wifi Adapter for Odroid for MRSD Project Course NSH B605 Team E Paul Calhoun
Camera Tripod and Universal Smartphone Moun	1	$11.95	$11.95	Tripod for MRSD Project Course NSH B605 Team E Paul Calhoun
Castle Creations CC Bec 10A 6S Switching Regulator	1	20,40	20,40	BEC for quadcopter for MRSD Project Course NSHB605 Team E Paul Calhoun
SparkFun FTDI Basic Breakout - 3.3V	2	$14.95	$29.90	Breakout board for quadcopter for MRSD Project Course NSHB605 Team E Paul Calhoun
USB 2.0 Cable - A-Male to Mini-B - 6 Feet	3	$4.34	$13.02	Cable for Arduino Nanos for MRSD Project Course NSHB605 Team E Paul Calhoun
Logitech Pro 9000	1	$139.96	$139.96	Camera for docking system for MRSD Project Course NSHB605 Team E Paul Calhoun
ARDUINO UNO REV3	2	$24.95	$49.90	Arduino controller for MRSD Project Course NSH B605 Team E Paul Calhoun

CarnegieMellon THE ROBOTICS INSTITUTE

MRSD Project – Dock-in-Piece

December 17, 2015

100 LB Holding Power Ceramic Cup Magnet	25	$2.47	$61.75	Magnets for Dock for MRSD Project Course NSH B605 Team E Paul Calhoun
USB 2.0 Extension Cable - A-Male to A-Female - 9.8 Feet (3 Meters)	4	$5.79	$23.16	USB Extension Cables for Data flow MRSD Project Course NSH B605 Team E Paul Calhoun
Dry Erase Markers	1	$7.09	$7.09	For MRSD Project Course NSH B605 Team E Paul Calhoun
DJI 1345s	10	$7.45	$74.50	Spare Propellors for quadcopter for MRSD Project Course B506 Team E Paul Calhoun
VELCRO Brand - Industrial Strength	1	$9.76	$9.76	Velcro for Dock for MRSD Project Course B506 Team E Paul Calhoun
SWITCH DETECT SNAPACT SPDT 30V	3	$1.86	$5.58	Limit switch for MRSD Project Course NSH B605 Team E Paul Calhoun
SW MINI SNAP ACTION .3A VERT 6V	5	$0.78	$3.90	Limit switch for MRSD Project Course NSH B605 Team E Paul Calhoun
Mounting Tape 3 Pack	2	9.24	$18.48	Mounting Tape for MRSD Project Course NSH B605 Team E Paul Calhoun
Tape 3 Pack	1	$4.73	$4.73	Tape for MRSD Project Course NSH B605 Team E Paul Calhoun
Half-size breadboard	2	$5.00	$10.00	Half size breadboard for dock for MRSD Project Course NSH B605 Team E Paul Calhoun
Smartphone tripod mount	1	$6.99	$6.99	Tripod Mount for MRSD Project Course NSH B605 Team E Paul Calhoun
Matrice Arm M1	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Paul Calhoun
Matrice Arm M2	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Paul Calhoun
Matrice Arm M3	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Paul Calhoun
Matrice Arm M4	1	$99.00	$99.00	Spare Arm for the quadcopter for MRSD Project Course B506 Team E Paul Calhoun
Tegg Paint Brush Set Acrylic 12pcs	1	$6.75	$6.75	Brushes for the dock for MRSD Project Course B506 Team E Paul Calhoun
SIX Color UV Reactive Invisible Acrylic Paint Set- 1/2oz pots	1	$19.95	$19.95	Paint for the dock for MRSD Project Course B506 Team E Paul Calhoun
DecoArt Americana Acrylic Paint, 2-Ounce, Slate Grey	1	$1.24	$1.24	Paint for the locking mechanism for MRSD Project Course B506 Team E Paul Calhoun
PCB	1	$187.95	$187.95	Quadcopter PCB on reimbursement
WiFi Module 3	1	$7.50	$7.50	WiFi module on reimbursement
Quadcopter Electronics		$29.99	$29.99	Electronics for Quadcopter on reimbursement
Dock Superstructure		$406.58	$406.58	L beams, nuts, bolts for superstructure on reimbursement

MRSD Project – Dock-in-Piece

December 17, 2015

Components				
TOTAL	$3835.44			